Laminae in the tropical middle stratosphere: Origin and age estimation

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Short title: LAMINAE IN THE TROPICAL STRATOSPHERE

Abstract. *In situ* measurements of N_2O and O_3 aboard the Observations from the Middle Stratosphere (OMS) balloon payload in the tropics are presented. In November 1997 at 7°S very distinct laminated structures in the N_2O profile were observed in contrast to earlier studies based solely on O_3 profiles. The laminae probably are an observation of Rossby wave-breaking events that lead to transport of mid-latitude air into the tropics. Using a photochemical model of the ozone response within those air parcels, their residence time in the tropics is estimated to be 4 to 6 weeks. In February 1997 at 7°S a similar vertical profile of N_2O revealed no mid-latitude laminae. We present dynamical arguments to support the existence of such laminae in November, but not in February.

1. Introduction

Isentropic transport of stratospheric air from mid-latitudes into the tropics has been a subject of considerable interest recently. This exchange process is important for the understanding of the distribution of trace gases and ozone, and for the prediction of the exhaust dispersion of a proposed fleet of high speed civil transport aircraft (HSCT), which would operate in the 15 to 20 km altitude range. A stratospheric transport barrier at about $\pm 15^o$ latitude (the latitude is variable) is indicated by a steep gradient in the distribution of long-lived tracers [e. g., *Tuck et al.*, 1997], by aerosol dispersion dynamics from tropical volcanic eruptions [e. g., *Trepte and Hitchman,* 1992], and by a change of slope for the O_3:NO_y correlation [e. g., *Murphy et al.,* 1993]. However, these features are difficult to represent in 2D models. Isolation of tropical from extra-tropical air is related to the rapid decrease with decreasing latitude of strong isentropic mixing by breaking Rossby waves in the mid-latitudes of the winter hemisphere. A model recently proposed by *Plumb* [1996], referred to as the "tropical pipe model", describes the implications of a tropical transport barrier for observed stratospheric tracer correlations. *Randel et al.* [1993] reported planetary-scale tongues of air at altitudes of 28 to 42 km moving from the tropics into mid-latitudes and related mid-latitude tongues extending into the equatorial region. Patches of the tropical air tongues will further stretch and eventually break off and can then irreversibly mix with mid-latitude air. These large scale intrusions of tropical air into the mid-latitudes have been modeled previously [e. g., *Waugh,* 1993]. *Randel et al.* noted that this kind of transport is "... mostly unidirectional - that is, material moves from the tropics to mid-latitudes but not vice versa". Nevertheless, estimates of transport rates of stratospheric air from mid-latitudes into the tropics have been made from correlations of long-lived tracers measured on the ER-2 aircraft [*Volk et al.,* 1996] and from vertical profiles of tracers measured from balloons, aircraft, and satellites [*Herman et al.*, 1998; *Minschwaner et al.*, 1996].

The OMS balloon program has acquired new data on tracer profiles both inside the tropical upwelling region and at mid-latitudes. We present N_2O and O_3 observations from the OMS balloon gondola showing what appear to be mid-latitude laminae entrained into the tropics. This is the first local observation of laminae in the middle stratosphere at tropical latitudes that are suggestive of processes responsible for global entrainment of mid-latitude air into the tropics. The time history of these laminae observed in the tropics is the subject of this paper.

2. Experimental

The concentrations of nitrous oxide (N_2O) and methane (CH_4) are measured by Argus, a second-harmonic, infrared absorption spectrometer using wavelength modulation of a tunable diode laser. Absorptions occur in a 26 cm base-path Herriott cell operating in a 72 pass mode. A beam splitter, sealed reference cell, and detector provide a separate spectrum of narrow N_2O, CH_4, and CO lines for accurate frequency calibration. The Argus enclosure is temperature controlled at 30 ± 7^oC to minimize drifts and temperature corrections to the data. Data are acquired at a rate of one complete atmospheric measurement per 16 seconds, resulting in a spatial resolution of about 40 m in balloon descent. The instrument is calibrated in the laboratory using accurately calibrated whole air standards. On the flight of 11 November 1997 a calibration standard was injected into the Herriott cell replacing the ambient air several times during the balloon descent. A Marquardt-Levenberg, non-linear least squares fitting scheme is used to obtain the methane and nitrous oxide number densities from the second harmonic spectra. Mixing ratios are deduced using the measured air density. A detailed error analysis indicates overall accuracy of 7% at 70 mbar, 8% at 50 mbar, and 10% at 20 mbar. The flight calibrations on 11 November 1997 and the comparison with ER-2 observations during a co-located flight on 30 June 1997 confirm this level of uncertainty in the data.

Figure 1 shows profiles of N_2O from balloon launches on 14 February 1997 at 7^oS

in Brazil (970214), 30 June 1997 at 65°N in Alaska (970630), and 11 November 1997 at 7°S in Brazil (971111). The data generally cover an altitude range from the upper troposphere to about 9 mbar (31 km). Two of the profiles show laminar structures that are certainly intrusions of air of different composition from that expected at the latitude of the measurement. Very low values of N_2O, close to 50 ppb, observed at 520 and 650 K potential temperature (55 and 32 mbar) on 970630, are attributed to remnants of the polar vortex from the previous winter. This interpretation is consistent with an identification of these air masses based on correlations of simultaneous measurements of CH_4 and N_2O from the OMS payload [*Herman et al.*, 1998]. Laminae of similar character, though at higher altitudes and with smaller N_2O perturbations, were observed at 850, 775, and 700 K on the tropical flight of 971111 and are interpreted as intrusions of mid-latitude air into the tropics.

3. Discussion

Figure 2 shows the scatter plot of O_3 [*Margitan*, 1998] versus N_2O for each flight shown in Figure 1. Also shown are the average correlation of O_3 [*Proffitt and McLaughlin*, 1983] versus N_2O [*Podolske and Loewenstein*, 1993] from ER-2 flights carried out at mid-latitudes and within the tropical upwelling region during the Stratospheric Tracers of Atmospheric Transport (STRAT) campaign. The ER-2 correlations, which extend only to $\approx$ 50 mbar (20 km), agree well with the OMS correlations.

To estimate how long the air masses in the laminae of 971111 have been in the tropics, we assume the air parcels moved isentropically from southern mid-latitudes, as typical heating rates of 0.6 K/day increase the potential temperature by less than 20 K/month. In response to enhanced UV radiation in the tropics compared to mid-latitudes, the ozone concentration is expected to increase. Since the local photochemical lifetime of N_2O is about a year at 30 km [*Minschwaner et al.*, 1993], we can neglect changes in the nitrous oxide concentration in this analysis. Neglecting transport and mixing of lamina air with neighboring air, the ozone concentration [O_3] will change according to

$$\frac{d[O_3]}{dt} = P - L[O_3] \tag{1}$$

where P is the ozone production in $cm^{-3}s^{-1}$, L the ozone loss rate in s^{-1}. This equation can be solved for the time the air parcel has resided in the tropics;

$$t - t_0 = -\frac{1}{L}(\ln([O_3(t)] - P/L) - \ln([O_3(t_0)] - P/L)) \tag{2}$$

where $[O_3(t_0)]$ is the ozone concentration before entering the tropics. P and L are kept constant over time and are calculated for 7°S using a photochemical model [*Volk et al.,* 1996] constrained by OMS measurements. The model ozone, methane, and temperature are initialized by the measured quantities, and NO_y is inferred from the Atmospheric Trace MOlecule Spectroscopy instrument (ATMOS) southern mid-latitude NO_y:N_2O correlation using Argus N_2O. The OMS H_2O measurements extend to $\approx$ 25 km. We calculate H_2O at higher altitudes assuming $2\times CH_4 + H_2O$ is constant at its 25 km value. Values for Cl_y and Br_y are estimated from Lightweight Airborne Chromatograph Experiment (LACE) F-11 measurments aboard OMS using correlations based on ER-2 measurements [*Wamsley et al.,* 1998 and references therein]. Photolysis rates are calculated for 7°S using measured O_3 up to the maximum altitude of 31 km and climatology above, and measured temperature.

We have characterized each of the laminae observed on 971111 by several properties: altitude, thickness or vertical dimension, and minimum N_2O value (Table 1). With the N_2O values measured in the lamina, we estimate the corresponding mid-latitude ozone concentration - hence $[O_3(t_0)]$ - from the ATMOS mid-latitude O_3:N_2O correlation observed during the ATLAS-3 mission in November 1994. A fit to the ATMOS mid-latitude observations is shown in Figure 2 and is used to calculate age "A" (Table 1). Under these assumptions the O_3:N_2O correlation in the lamina changes with time, as indicated by the arrow in Figure 2, after the air entered the tropics. Age "B" is calculated from $[O_3(t_0)]$ determined by the lower edge of the span of the individual ATMOS O_3:N_2O data points (Figure 2). If instead we estimate $[O_3(t_0)]$ using the mean ATMOS mid-latitude O_3 profile at the same potential temperature surface (not shown), we find slightly shorter timescales. Age "A" represents the most likely starting condition for O_3, and age "B" represents the lowest possible starting condition for O_3, and consequently an upper limit for age. Since the observed correlation lies within the range of mid-latitude ATMOS correlations the lamina air could have entered the tropics very recently (i. e. age = 0 days). A comparison of the measured amount of N_2O in each lamina and the mean N_2O profile observed at mid-latitudes is used as a qualitative guide to the degree of mixing of lamina air with surrounding air masses.

Lamina 1 at $\approx$ 700 K has a very clear N_2O signature, whereas the O_3 signature is less obvious due to the steep increase in the ozone volume mixing ratio (VMR) with altitude. The photochemical age of this lamina for the two different initial ozone concentrations are 30 or 46 days, respectively. Note that this lamina could be older than this upper limit if the ozone had already reached equilibrium, though we believe there is still some signature in the ozone profile. The measured N_2O in the lamina is similar to the mid-latitude ATMOS N_2O VMR at the same potential temperature and supports the assumption of little mixing since this mid-latitude air parcel entered the tropics.

Lamina 2 is a small, though clearly present perturbation to the ozone and N_2O profiles at 775 K. Comparing the N_2O in the lamina with the mean mid-latitude ATMOS value at 800 K suggests a mixture of about 2/3 tropical air and 1/3 mid-latitude. Since we have no way to estimate when the mixing happened, the 40 days photochemical lifetime for this lamina is an upper limit and is most likely too long.

Lamina 3 at 850 K has a distinct signature in both N_2O and O_3. The photochemical age is 28 and 36 days, respectively. Depending on the strength of large scale shearing motions this lamina might still show a clear signature in N_2O in a few weeks, whereas the ozone will have recovered to equilibrium. Comparison of the N_2O with the ATMOS profile suggests there has been substantial mixing of tropical air into this lamina (about 1/3). This observation could be attributed to a vertical mixing event, caused by a passage through a region of breaking topographically or convectively generated gravity waves. An alternative explanation for the tracer characteristics of lamina 3 entails mixing of tropical air with extra-tropical air at higher latitudes prior to entrainment or re-entrainment into the tropics.

Sensitivity studies show that the calculated ages depend on NO_y, O_3, and temperature, but only slightly on H_2O, Cl_y, Br_y, and J-values. The uncertainties in the estimated age are considerable when the equilibrium $O_3 = P/L$ approaches the measured O_3 in the laminae. For lamina 3 we find changing the NO_y by $+-2$ ppb (estimated uncertainty in NO_y based on variance of ATMOS data) changed the age "A" by -7 and $+21$ days. For the other laminae the variation is less than 5 days for the same change in NO_y.

The laminae presented here are probably the result of Rossby wave breaking events. During November 1997 in the southern hemisphere, winds at middle and high latitudes are still westerly. Final vortex breakup occurred around November 15-20 in 1997. Thus, planetary waves propagate to this altitude and break as they approach the low latitude critical line [*Andrews et al.*, 1987]. In February 1997, however, summer easterlies prevail in the southern hemisphere, blocking the propagation of planetary waves from the troposphere [e.g., *Waugh*, 1996]. Thus very little lamination is expected and none was observed on 970214. Also, 7°S is much closer to the "edge" of the tropical reservoir of N_2O in November than February [e.g., *Randel et al.*, 1994]. Laminae are much more likely near regions of strong horizontal gradients.

From this one flight it is not possible to estimate the global entrainment of mid-latitude air into the tropics. More measurements in the tropics are needed to provide adequate statistics for a global estimate. Potentially, more flights with a full tracer package could allow us to investigate laminated structures found in the ozone profile. *Reid and Vaughn* [1991] and more recently, *Grant et al.* [1998] reported statistics of tropical ozone soundings. In contrast to this work, *Grant et al.* found laminae to be constrained to below 21 km and "no statistically significant Rossby wave activity".

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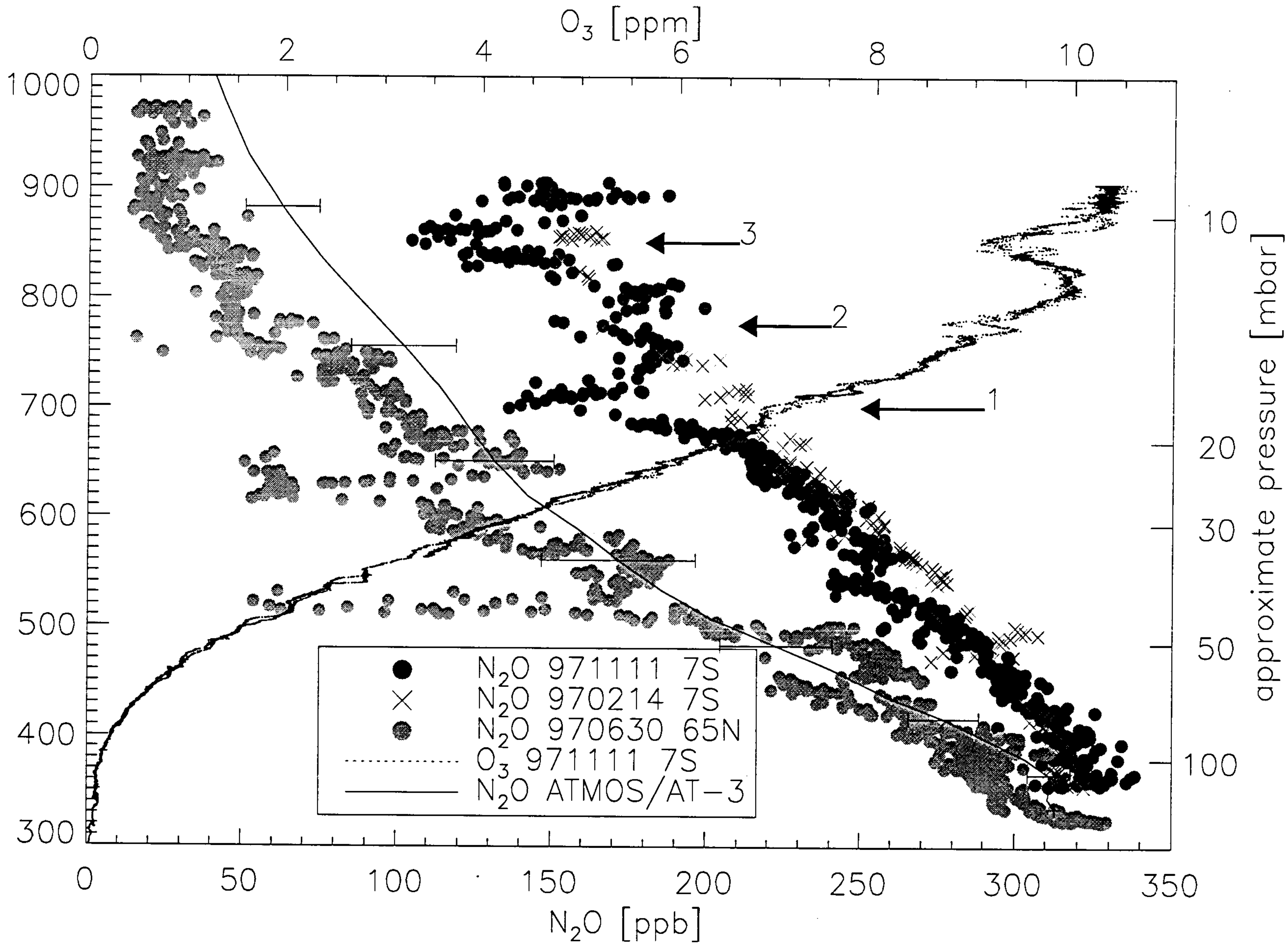
Figure 1. Profiles of Argus N_2O: 970214 at 7°S (gray x), 970630 at 65°N (light gray) and 971111 at 7°S (black), mean ATMOS/ATLAS-3 mid-latitude profile (solid line) and O_3 on 971111 (use upper x-axis). Error bars on the ATMOS data represent one standard deviation. The labels correspond to the laminae numbering in Table 1. The pressure axis on the right hand is for the tropical flight.

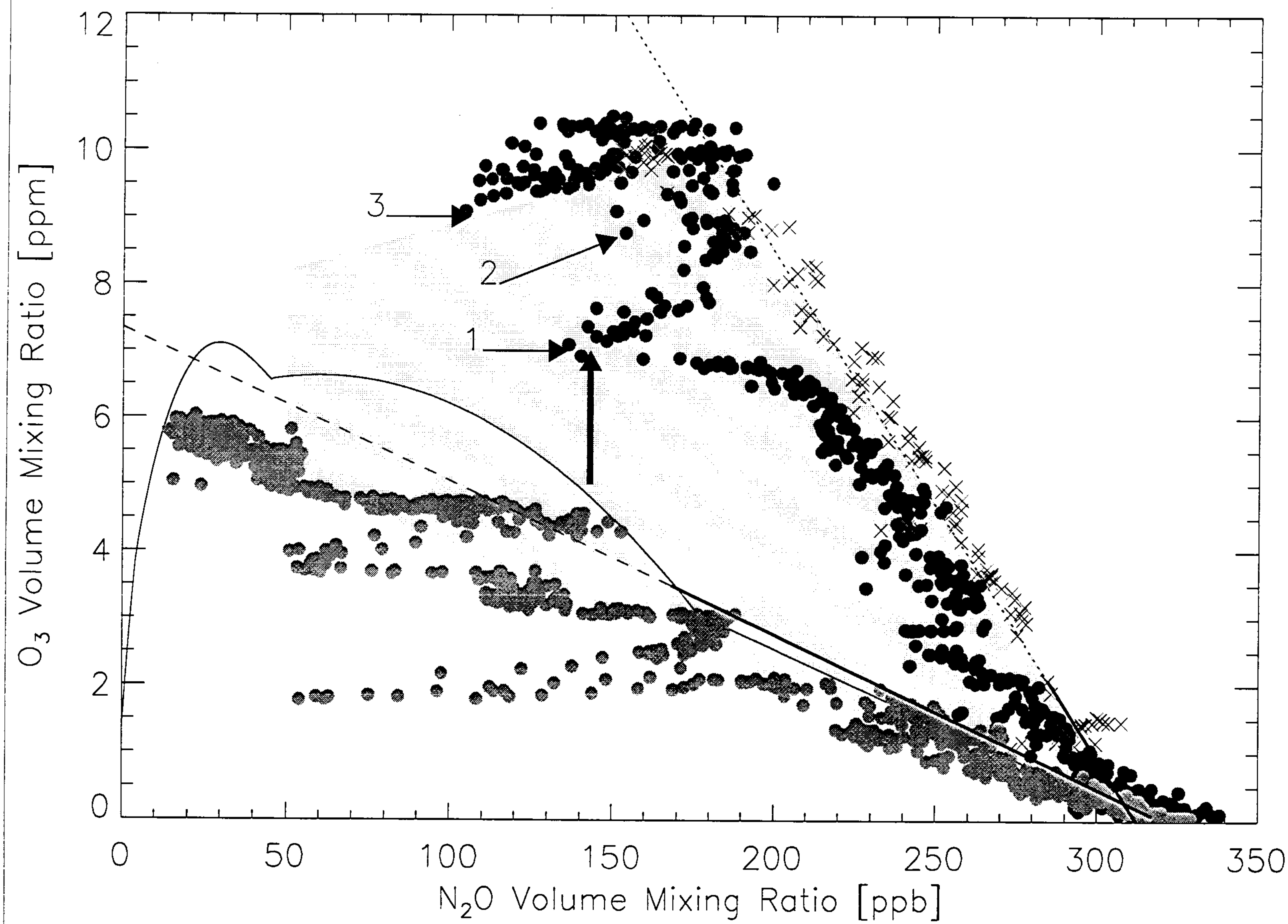
Figure 2. Correlation of O_3:N_2O for 970214 at 7°S (gray x), 970630 at 65°N (light gray) and 971111 at 7°S (black). Mean ER-2 tropical O_3:N_2O correlation (dotted) and mid-latitude O_3:N_2O correlation (dashed). The heavy solid part of the lines indicates the actual measurement range of the ER-2. Fit to ATMOS mid-latitude O_3:N_2O correlation (solid). The shaded area represents the spread of the individual O_3:N_2O ATMOS observations (5° - 50°). The numbered arrows identify the laminae listed in Table 1.

Table 1. Characteristics of laminae observed at 7°S on 971111: approximate altitude, approximate potential temperature θ, pressure, minimum N_2O volume mixing ratio, thickness and residence time calculated using Equation (2). For the age "A" calculations ATMOS mid-latitude O_3:N_2O correlations and for "B" the lower edge of the shaded area in Figure 2 were used, respectively.

	approximate						
	altitude km	θ K	pressure mbar	N_2O ppb	thickness km	age A days	age B days
1	27	700	18	138	0.5	30	46
2	29	775	13.5	153	0.2	36	41
3	30.5	850	11	108	1.0	28	36



O3 [ppm]
0
2
4
6
8
10
1000
900
800
700
600
500
400
300
10
20
30
50
100
approximate pressure [mbar]
3
2
1
N2O 971111 7S
N2O 970214 7S
N2O 970630 65N
O3 971111 7S
N2O ATMOS/AT-3
0
50
100
150
200
250
300
350
N2O [ppb]



O3 Volume Mixing Ratio [ppm]
N2O Volume Mixing Ratio [ppb]
0
2
4
6
8
10
12
50
100
150
200
250
300
350
1
2
3